



A spatial assessment of potential biomass for bioenergy in Australia in 2010, and possible expansion by 2030 and 2050

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Abstract

This paper provides spatial estimates of potentially available biomass for bioenergy in Australia in 2010, 2030 and 2050 (under clearly stated assumptions) for the following biomass sources: crop stubble, native grasses, pulpwood and residues (created either during forest harvesting or wood processing) from plantations and native forests, bagasse, organic municipal solid waste and new short-rotation tree crops. For each biomass type, we estimated annual potential availability at the finest scale possible with readily accessible data, and then aggregated to make estimates for each of 60 Statistical Divisions (administrative areas) across Australia. The potentially available lignocellulosic biomass is estimated at approximately 80 Mt per year, with the major contributors of crop stubble (27.7 Mt per year), grasses (19.7 Mt per year) and forest plantations (10.9 Mt per year). Over the next 20–40 years, total potentially available biomass could increase to 100–115 Mt per year, with new plantings of short-rotation trees being the major source of the increase (14.7 Mt per year by 2030 and 29.3 Mt per year by 2050). We exclude oilseeds, algae and 'regrowth', that is woody vegetation naturally regenerating on previously cleared land, which may be important in several regions of Australia (*Australian Forestry* 77, 2014, 1; *Global Change Biology Bioenergy* 7, 2015, 497). We briefly discuss some of the challenges to providing a reliable and sustainable supply of the large amounts of biomass required to build a bioenergy industry of significant scale. More detailed regional analyses, including of the costs of delivered biomass, logistics and economics of harvest, transport and storage, competing markets for biomass and a full assessment of the sustainability of production are needed to underpin investment in specific conversion facilities (e.g. *Opportunities for forest bioenergy: An assessment of the environmental and economic opportunities and constraints associated with bioenergy production from biomass resources in two prospective regions of Australia*, 2011a).

Keywords: Australia, bioenergy, biofuel, biomass, spatial biomass assessment

Received 10 March 2015; revised version received 11 June 2015 and accepted 4 July 2015

Introduction

Current and future biomass production in Australia could support a significant contribution to renewable energy in Australia (Farine *et al.*, 2012). Bioenergy can take the form of bioelectricity, heat and biofuels (solid, liquid or gas). Farine *et al.* (2012) outlined why much of the international literature estimates of the Australian resource base for bioenergy are not robust. This previous study (Farine *et al.*, 2012) provided spatial and temporal estimates of biomass production for several different categories of biomass, as well as potential availability and use within several different types of

bioelectricity and biofuel conversion technologies in Australia. The Farine *et al.* (2012) paper provided a valuable first step towards quantifying the bioenergy potential and greenhouse gas mitigation that could be provided in Australia, but did not provide regional-scale estimates of the biomass production and potential availability within various regions of Australia. RIRDC (2011) lists 'the identification of regions for the sustainable growing of bioenergy/biofuel crops and integrated biomass production' as a research, development and extension priority for primary industries in Australia.

Regional studies with specific biomass feedstocks and target technologies have been completed for some areas of Australia (e.g. Rodriguez *et al.* (2011a) for Gippsland and lignocellulosic ethanol; Rodriguez *et al.* (2011b,c) for Green Triangle and small-scale bioelectricity and lig-

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nocellulosic ethanol; Murphy *et al.* (2015) and Hayward *et al.* (2015) for Fitzroy and lignocellulosic biocrude to jet fuel, diesel and gasoline). These regional-scale spatial and temporal estimates of biomass production and potential availability are required to underpin the development of industry based on local conversion facilities, because the economies of scale depend on the distributional density of the aggregate amount of biomass feedstocks relevant to the particular conversion technology. Optimizing the scale and type of energy facility or biorefinery to the distribution, location, spatial density and seasonal supply of biomass is critical. The above case studies (Rodriguez *et al.*, 2011a,b,c; Hayward *et al.*, 2015; Murphy *et al.*, 2015) looked at subsets. Furthermore, Brinsmead *et al.* (2015a,b) developed quantitative methods to optimize the locations of bioenergy facilities. The missing link is information on distribution, location, spatial density and seasonal supply at regional scale across the country. This paper provides information at an intermediate scale between a national assessment and a specific business case (regional) scale that helps to fill the gap.

This paper aims to assist with industry development through a better understanding of the distributions of different biomass types. It is based on recent work by Crawford *et al.* (2012). It builds on the analysis from Farine *et al.* (2012) by including additional biomass types (grasses and waste), extended time-frames (to 2050) and by providing a spatial disaggregation that enables comparative estimates of different biomass types. We estimate the amounts of each biomass type within Australia-wide Statistical Divisions (SDs) as set out by the Australian Bureau of Statistics (ABS) (Edwards, 2001) to identify regional areas of high potential for development of a bioenergy industry – the biomass hotspots. The amounts reported are what is potentially available allowing for ongoing sustainable supply. No allowance has been made for any current uses of these products, Rodriguez *et al.*, 2011b,c and Farine *et al.*, 2012 have discussed some current uses of stubble, bagasse and sawmill wastes. Rodriguez *et al.*, 2011a,b,c have produced biomass supply curves, and Brinsmead *et al.*, 2015a,b have examined how to optimize plant size and type.

There are several types of biomass produced in Australia, and significant quantities could be used for bioenergy. In this paper, we provide estimates of the amount of biomass produced annually in 2010, projected to 2030 and 2050. We apply explicit assumptions (and underlying rationale) to estimate the components and proportions of the biomass produced which could be potentially available for each of the following biomass types:

- Crop stubble – field residues from grain crops
- Grasses

- Wood (pulp logs, in-field woody harvest residues and wood processing residues) from plantations and native forests
- Bagasse – residue remaining after processing of sugar cane
- Waste – organic components of municipal solid waste (MSW)
- Biomass from newly established short-rotation tree crops (SRT)

The estimates are produced from the following analytical steps:

- **Biomass production:** Assessment of annual production, either as reported by others or as estimated by modelling. Different approaches are used for each different type of biomass as appropriate to that form.
- **Potentially available for harvest:** application of simple constraints to the total production (e.g. technical constraints to harvesting stubble or grasses; environmental constraints for leaving some soil cover).
- **Potentially available for diversion:** in the case of those existing types of biomass which are already harvested and consumed in an existing market (e.g. pulpwood, bagasse), simple constraints applied (e.g. diversion of all of the pulp logs, but none of the sawlogs from existing markets).

Assumptions and constraints are detailed further by Farine *et al.* (2012). We present only the 'potential' availability estimates: the actual availability of biomass will depend on many local factors which are beyond the scope of this study, including the technologies and economics of growing, harvest and transport; willingness of growers to adopt new technologies or markets and participate in new or emerging supply chains; local planning and legislative constraints. Security of biomass supply is a critical issue for the investors in the bioenergy facility (Sims *et al.*, 2008; Richard, 2010). We demonstrate and discuss the year-to-year variation in the availability of crop residues and grass biomass caused by climatic variability over a 20–30 year period.

Over the last 25 years or more, there has been a large amount of research examining the incorporation of trees into the landscape in various configurations ranging from block plantings to narrow rows for a range of uses including biodiversity restoration, salinity reduction and biomass production (Wildy *et al.*, 2004; Bartle, 2009; Bartle *et al.*, 2007). The SRT system of growing a woody crop that is harvested every 5–10 years for its lignocellulosic product has been identified by RIRDC (2014) as a potential feedstock worthy of further development for

the bioenergy sector. We have modelled the SRT system as described in Farine *et al.* (2012).

Previous studies in Australia have demonstrated that the production of plant-based oils (from oilseed crops, trees such as *Pongamia*, and algae) is projected to remain low in the next decade or two at least (Farine *et al.*, 2012; Murphy *et al.*, 2012). Therefore, this paper focuses on the more immediate opportunities presented by lignocellulosic biomass.

One large potential source of lignocellulosic biomass that is not considered in this paper is native woody regrowth vegetation which originates after clearing for agricultural development. Booth *et al.* (2014) have estimated the production of regrowth for the Fitzroy Region, Queensland, and however, national spatial estimates of potential biomass production and potential availability of native woody regrowth have not been conducted yet.

Due to the dispersed nature and high level of variability of lignocellulosic biomass production systems, we believe that security of supply can most appropriately be met by an industry which can use mixed lignocellulosic feedstocks, including annual and perennial biomass sources. This will increase the critical mass of total potentially available feedstock concentrated within economic distance, deal with temporal issues such as seasonal variation or drought, and thus avoid the risk of relying on a single feedstock type.

It is relatively simple to calculate current and estimate future biomass production for existing commercial types of biomass using published statistics at a national or state level. However, the differing scales and types of regional reporting (or lack of any reporting in some cases) makes it more difficult to provide the finer scale spatial and temporal assessments of biomass production and potential availability which are required to support industry development in any given region. The estimates of new types of biomass, for example SRT, cannot be derived from reported statistics and are therefore more uncertain. Some biomass sources are widely distributed with a low biomass density or are seasonal in their production or potential availability. Using a common reporting structure, different biomass types then can be aggregated to estimate regional biomass totals.

Materials and methods

This paper uses spatial analysis techniques to map each biomass type according to its original reporting structure and then convert it to a common reporting structure – SDs. The SD boundaries are reviewed every 5 years to coincide with the Australian Population Census, although boundary changes are usually minor. This study used the 2006 SD layer which has 60 individual SDs with size varying from 800 to 1 345 000 km² and in aggregate; they cover the whole of Australia. A 61st SD

which covers island territories (Christmas and Cocos Islands) to the north-west of mainland Australia was not included in this study. Table S1 includes each SD identification number and name.

For each biomass type, we made spatial estimates for the amounts potentially available at the finest spatial resolution possible, using the methods described below.

Crop stubble

In Australia, statistics on the annual production of agricultural commodities are compiled by the Australian Bureau of Statistics (ABS) based on censuses and surveys. Broad acre crop residues remaining after harvest (referred to here as crop stubble) were estimated from annual grain production statistics and harvest index data (the ratio of grain to total above-ground biomass) and converted to dry mass (assuming 15% moisture content) (Herr *et al.*, 2010). Further details, including rationale for retention of some crop residue for soil protection, are provided in Herr *et al.* (2012a) and Farine *et al.* (2012). There is large interannual variability in crop yields and thus stubble production. Figure 1 illustrates the average crop stubble production potentially available for harvest (PAfH) for 1983–2005. Prior to the mid-1990s, Australia experienced an expansion in grain production areas. This study used the 1996–2005 time period to be consistent with Farine *et al.* (2012) and because areas under grain production stabilized in the mid 1990s.

Estimates of the stubble PAfH were made nationally at the 2002 SD level of spatial resolution. Differences in SD boundaries over time were dealt with by converting the data to a common SD layer prior to aggregation (J. Walcott, pers. comm., Bureau of Rural Sciences). Estimates of stubble PAfH from wheat, oats, barley, triticale, sorghum, canola and lupins were combined for each SD. The 2001/02 Australian land-use layer (Knapp *et al.*, 2006, 50 m resolution) was used to extract the appropriate cropping land-use pixels, *viz.* the aggregation of irrigated and nonirrigated cereals, oil seeds and legumes to give the number of crop stubble pixels. For each 2002 SD, the crop stubble PAfH estimate was divided by the SD crop stubble pixel number to get a harvestable yield per pixel. Using a GIS, the crop stubble PAfH for the 2002 SD layer was converted to crop stubble PAfH for the 2006 SD layer. Figure 2 illustrates the spatial concentration of the resource based on focal statistics, where each pixel is the sum of stubble biomass PAfH within a 50 km radius. The underlying spatial data used is the average stubble PAfH for 1996–2005 at 10 km resolution. This focal analysis (Fig. 2) can assist with the visualization of areas of high concentration for a widely distributed resource such as crop stubble. Further details on land use and methods for overlaying polygons of different size/shape to transfer values are described elsewhere (Herr, 2007; Herr & Dunlop, 2011).

Grasses

Herr *et al.* (2012b) made broad model-based estimates of grass production across Australia and concluded that there is a potential for grasses growing outside the existing cropping and hay production areas to provide a bioenergy feedstock. Here,

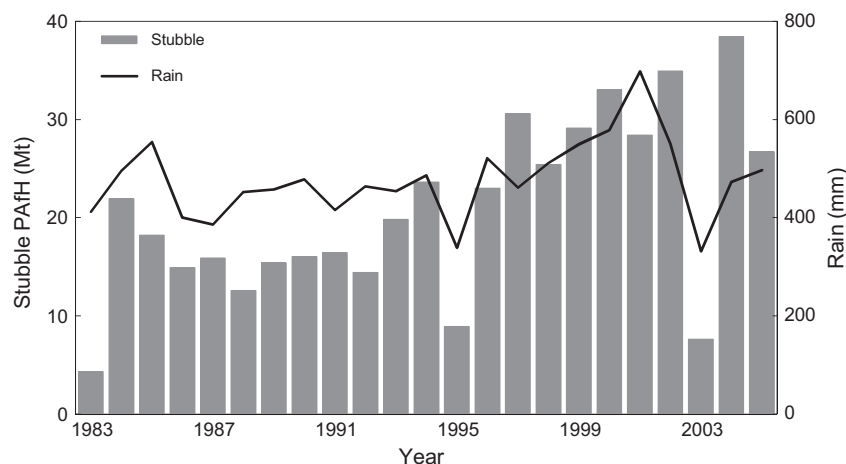


Fig. 1 Variation in annual rainfall and the amount of crop residue potentially available for harvest (PAfH) across Australia for the period 1983–2005 (derived from Herr *et al.*, 2012a).

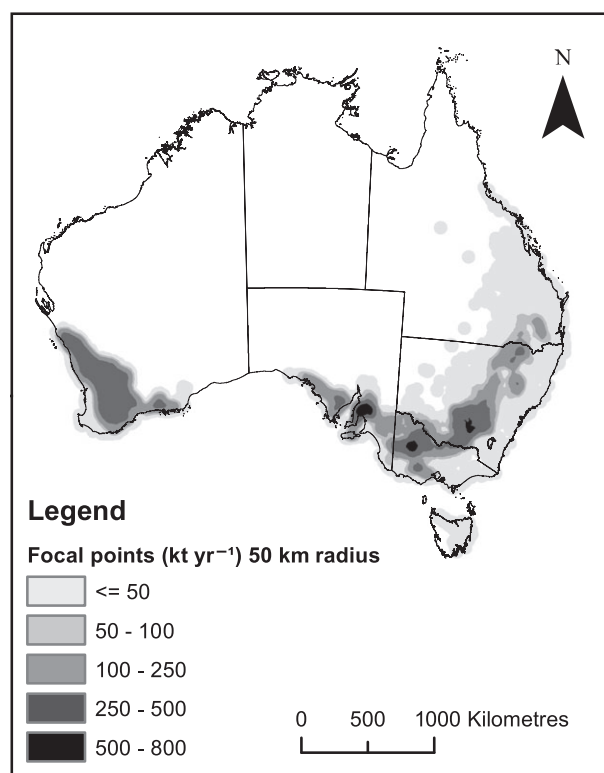


Fig. 2 Average crop stubble biomass (kt yr^{-1}) focal concentrations for the period of 1996–2005.

we applied the model AussieGRASS (Carter *et al.*, 2000, 2003; see <http://www.longpaddock.qld.gov.au/about/researchprojects/aussiegrass/index.html>) to generate spatial estimates of net primary production (NPP) and standing (potentially harvestable) biomass modelled at a resolution of 5 km. AussieGRASS estimates pasture biomass, which includes native and introduced grasses and forbs.

This paper applied the same constraints for grass calculation as in Crawford *et al.* (2012), which was based on estimating pasture productivity with AussieGRASS (Carter *et al.*, 2000, 2003; Murphy *et al.*, 2015): grass would only be harvested when economic to do so, and some cover also needs to be retained for soil protection (standing biomass $\geq 5.5 \text{ t ha}^{-1}$ and retaining 2.5 t ha^{-1} leaving at least 3 t ha^{-1} for harvest for efficiency reasons in harvesting). In general, the decrease in hay harvesting cost stabilizes at around 3 t ha^{-1} , which is related to the greater efficiency with increased yield, as fixed costs for machinery and labour decrease when spread over a larger harvest. Retention for soil protection is to ensure that residual total standing dry matter (TSDM) after harvest could maintain 40% ground cover. We acknowledge these constraints will need refinement when a more detailed case study is carried out in the future. Only pasture and grazing lands from the Bureau of Rural Sciences (BRS; now formerly merged with the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)) land use of Australia (BRS, 2010) were included in the calculations. Areas considered to be practical to harvest required tree basal area per ha to be less than 0.1% (very low tree density) and slope to be less than 12 degrees. The biomass that was potentially available for harvest (PAfH) was calculated for each year over a period of 30 years (1981–2010), and also as an average over that period. PAfH grass biomass was aggregated for each 2006 SD polygon.

Plantation forests

An Australian Government programme – the National Plantation Inventory – has been collecting and reporting on plantations established primarily for wood production since 1993. Comprehensive plantation log supply forecast reports have been produced every 5 years. We used the Gavran *et al.* (2012) forecasts for pulp log and sawlog supply (wood volume) for hardwood and softwood plantations for each of the 15 Australian National Plantation Inventory (NPI) regions on an annual basis for 5-year periods. These estimates were used to

provide current and future estimates of plantation wood flows. As plantation planting rates have varied through time, especially with the more recent hardwood plantation establishment, estimated wood flows can vary between time periods. The following three periods were taken to approximate log flow for the three time periods used in this study: period 2010–14 = 2010, period 2030–34 = 2030, period 2050–54 = 2050. Wood volumes were converted to dry mass using average densities of sawlogs and pulp logs from hardwood and softwood plantations as described in Farine *et al.* (2012).

Ximenes *et al.* (2008) estimate that, in Australian softwood and hardwood forests, as much as 30–55% of the above-ground biomass is left on site following commercial harvest. Following harvest, Ximenes *et al.* (2012) estimated that for 16 plots of *P. radiata* plantations of various ages and silvicultural treatments at four sites; the harvest residue of waste logs, stumps and large branches was 7.5–13.7% of the harvested log mass. In eucalypt plantations in southern Queensland, it was estimated that unmerchantable stemwood for solid wood products could be as much as 25–50% of the timber harvested (Meadows *et al.*, 2014). For this study, in-field woody residues (harvest residues – includes woody stems and large branches) that could be recovered for bioenergy were calculated as 9% of harvested log mass; all other residue components (smaller branches, leaves, etc.) were assumed to be retained in the forest for environmental reasons such as site nutrient retention and habitat (Farine *et al.*, 2012). Sawmill residues were calculated as a fraction (range 57.4–67.4%) of the processed sawlog mass, based on state data from industry surveys (Burns *et al.*, 2009). We assumed that 100% of the pulp log, sawmill residue and in-field woody residue would be potentially available for bioenergy.

Using a spatial map of Australian plantation forests (ABARES, 2008), the areas of hardwood and softwood plantations were estimated for each NPI region. We assumed that there would be no change in the areas of hardwood and softwood plantations into the future. The amount of pulp log, sawmill residue and in-field woody residue biomass for hardwood and softwood for each NPI region was then divided by the appropriate forest area to give an average amount of biomass/unit area for each NPI region at each time period. We examined three biomass types (pulp log, sawmill residue and in-field woody residue) from both hardwood and softwood plantations.

The 2006 SD polygon layer was overlaid on the spatial plantation type x NPI region data, and a new spatial layer was produced giving the area of softwood or hardwood plantation in each NPI region by each SD polygon. These areas were multiplied by the biomass/unit area values for each biomass type x NPI region to get potentially available forest biomass for bioenergy for each SD polygon. Amounts were summed to give the total potentially available biomass from forest plantations for each SD for each time period.

Native forests (NF) managed for sawlog production

Sixteen per cent of Australia's native forest is now formally protected in public conservation reserves. Timber harvesting is

generally permitted in multiple-use native forests, which cover around 6% of Australia's total native forest estate (Montreal Process Implementation Group for Australia, 2008). The following procedures were used to estimate the amount of potentially available biomass in each SD polygon.

A map of production native forests (Bureau of Rural Sciences, 2010) was overlaid with the SD polygons. The major production native forests are distributed within relatively few regions in south-east (SE) mainland Australia, SE Queensland, south-west (SW) of Western Australia and in Tasmania. We applied our broad knowledge of forest distribution and forest management (Raison & Squire, 2010), and findings from other regional studies (Rodriguez *et al.*, 2011a), to approximately allocate state-level estimates (ABARE, 2010) of the annual volumes of sawlog and pulp log harvest from native forests to the appropriate SD polygons. Wood volumes were converted to dry wood mass as described above for plantation forests (see also Farine *et al.*, 2012). Sawmill residues were calculated as a fraction (range 59.9–67.4%) of the processed sawlog mass, based on state data from industry surveys (Burns *et al.*, 2009).

In native forest harvest operations, 'residual' logs may be left on the ground – these trees are felled as a part of normal harvesting operations, but for several reasons are normally non-commercial (e.g. they contain decayed wood or are not species of interest). These residual logs and other in-field woody residue were estimated as 60% of harvested logs (Raison & Squire, 2010; Rodriguez *et al.*, 2011a). All other harvest residues (branches and leaves) were assumed to be retained in the forest.

We assumed that 100% of the pulp log, sawmill residue, residual log and in-field woody residue would be potentially available for bioenergy and that the amounts of biomass potentially available in 2010 will remain the same until 2050. Amounts for each biomass type were summed to give the total potentially available biomass from native forests for each SD and time period.

Bagasse

In Australia, sugarcane production occurs in coastal hubs between Mossman in far north Queensland (Qld) and Grafton in northern New South Wales (NSW). Bagasse is the residue remaining after the crushing of wet cane and extraction of sugar. The quantity of bagasse potentially available was estimated from sugar industry production statistics (1996–2005) for the five reporting regions where sugar cane is grown (Anon, 1996–2006; ASMC, 1996–2006) (*viz.* Northern, Herbert/Burdekin, Central, South Queensland and NSW). Wet cane yields were adjusted to account for sugar extracted, and for moisture content to estimate the amounts of dry bagasse produced (equivalent to ~15% of the weight of wet cane).

The SD polygons were overlaid on the sugar production regions; for four of the five regions, all sugar mills associated with the region were contained by a single SD region. For the South Queensland region, the Rocky Point sugar mill fell into a different SD from the other regional mills. The bagasse production for the South Queensland region was split proportionally across the two SDs based on individual mill production data

(Canegrowers, 2006). It was assumed that 100% of bagasse would be potentially available for bioenergy. Trash remaining in the field after cane harvest was not considered to be PAFH as an energy source.

Waste

Waste is defined here as 'any discarded, rejected, unwanted, surplus or abandoned matter...' (DEWHA, 2010; p. 361) that may be intended for disposal, recycling, reprocessing or recovery. Organic waste includes all materials that originate from living things and includes food waste, garden waste, paper and cardboard. These organic wastes are of interest for bioenergy production and can be found in three waste streams:

1. Municipal solid waste (MSW) which is primarily waste collected from households and councils, mostly through kerbside collection and recycling
2. Commercial and industrial (C&I) waste which is mainly collected from commercial buildings, government facilities, educational institutions and industrial sites
3. Construction and demolition (C&D) waste which is residential, civil and commercial waste, produced by demolition and construction of buildings (some waste from residential renovations may end up in the MSW stream) (DEWHA, 2010).

Waste management in Australia is undertaken by local governments and is legislated by state governments. Each jurisdiction differs in what is recycled and what records are kept for materials that are recycled or disposed into landfill, making consistent comparisons across the country extremely difficult. Over 90% of Australian households have some sort of kerbside recycling service (DEWHA, 2010); this greatly facilitates the recovery of particular materials from the waste stream. Whilst all jurisdictions are working towards waste minimization and increased recycling, the recycling facilities available to households vary considerably both within a state and between states.

A recent review (Hyder, 2011) identified 23 different waste classification systems and various data capture methods across Australia. Hyder (2013) have since reported on the waste information gaps. As a result of some states employing more than one classification scheme, it can be difficult to aggregate waste to a state level for all streams. Waste is typically measured at landfill and recycling sites, which act to concentrate material from changing catchment areas which are thus not easily matched to SDs. Whilst averaging over a decade or more is valid for agricultural and forestry biomass, where the geographic footprint of these sources is relatively stable, time-series data for waste is more difficult to average. The 'footprint' for waste collections is continually changing as urbanization and population increases, availability of recycling options is expanded and data collection is improved. These data, within a harmonized system for national waste reporting as recommended by Hyder (2013), should improve the estimation of organic waste production in the future.

A total amount of 43.7 Mt of waste is estimated to have been generated in Australia in 2006–2007 (DEWHA, 2010: table 2.2). Of this total, about half is recycled and half disposed in landfills (DEWHA, 2010: table 2.5). Hyder (2009) reported on

material disposed and recycled (i.e. total waste generated) in the three waste streams for 2006–2007 disaggregated to the state/territory level. We combined data from Hyder (2013) and DEWHA (2010) to estimate the amount of organic waste biomass per waste stream per state/territory. The 'organic fractions' used were paper and cardboard, garden waste, food waste and wood/timber where these categories were reported. Wood and timber from the C&I waste stream were excluded to avoid double counting of forestry material. The moisture content of different fractions is mostly unknown. Reported masses were used without any moisture correction, except for food waste which was reduced by 50%.

Population data and per capita organic waste generation were the basis for disaggregation of organic waste amounts from state/territory to SD level. We excluded C&D and C&I organic waste from disaggregation to SD level on the basis that only the MSW waste stream is primarily collected from households (DEWHA, 2010) and is therefore approximately correlated to population, whereas data correlating C&D and C&I waste to population do not currently exist for the whole of Australia. SDs can be broken down into smaller units called statistical local areas (SLAs). We used population estimates at the SLA level (2006) for current (treated as equivalent to 2010 in this study) and future (2030 and 2050) time horizons from the Base Case scenario for SLA population to 2100 developed for a recent study of Australian coastal climate risk (Baynes *et al.*, 2012). Key inputs to Baynes *et al.* (2012) are the 2006–2026 projections from the (then) Federal Department of Health and Ageing which have now been superseded by the 2011–2026 SLA projections available from the Department of Health (<https://www.health.gov.au/internet/main/publishing.nsf/Content/ageing-stats-lapp.htm>), and is based in turn on ABS population projections 2006–2100 (ABS, 2008). SLA current and future populations were aggregated for each 2006 SD polygon to give SD population at 2010, 2030 and 2050. Per capita waste was calculated by dividing each state/territory MSW organic waste total by its population, then multiplying by SD population to give total waste biomass in each SD. The final amounts are likely to be an underestimate of the total amount of waste biomass.

New plantings of short-rotation trees (SRT)

There is potential to establish significant areas of new woody plantings, integrated with traditional agriculture, for production of biomass for bioenergy. Such plantings could be grown on short (<10 years) rotations and would often utilize coppicing (re-sprouting) species. We examined the following expansion scenario: planting of 5% of cleared farmland (~2.4 Mha) by 2030 and extension of the area to 10% (~4.8 Mha) by 2050. It was assumed that there would be no significant reduction in stubble or grass production as the total area diverted to SRT is relatively small. However, the tradeoffs involved would be complex and very specific to the region, biomass and agricultural production system, and the particular spatial arrangements (e.g. block v row plantings) in a given landscape. For example, in some situations, rows of mallee trees have been shown to reduce crop or pasture production by up to 52% within 11–12 m of the trees (or 2.6 times tree height) and by

35% within 20 m (Peck *et al.*, 2012). This competition zone may be reduced for the first three or so years following tree harvest. Whereas in other situations, there may be significant benefits to the agricultural production system (e.g. increased grain production) due to improved shelter and salinity benefits of tree plantings (Stirzaker *et al.*, 2002). These issues require further exploration to underpin feasibility studies at a more local scale.

Biomass production was estimated spatially using the Physiological Principles Predicting Growth (3-PG) model (Landsberg & Waring, 1997) that has been calibrated for relevant SRT species (3-PG2, Polglase *et al.*, 2008). The scenario used in this study relied on a stocking rate of 2500 stems ha⁻¹ and a rotation length of 5 years. Further details of the methods used are described in Rodriguez *et al.* (2011a) and Farine *et al.* (2012). Land with mean annual rainfall >275 mm yr⁻¹ was identified within the nonirrigated crop and sown pasture lands from the BRS land use of Australia layer (Bureau of Rural Sciences, 2010).

This land layer was used to extract cells from the SRT 3-PG2 modelled output. Spatial layers of annual total above-ground biomass production were produced. These biomass layers were then overlaid with the SD polygon layer. Annual biomass production was then determined for each SD polygon for the 5% and 10% planting scenarios for the 2030 and 2050 time periods, respectively. The total area of this category of land was 48 million hectares and the area modelled to be planted to SRT was (2.4 Mha) by 2030 and (4.8 Mha) by 2050.

Results

Crop stubble

The distribution of Australia's agricultural production systems and estimated annual production of crop stubble has been reported by Herr *et al.* (2012a). The crop stubble PAFH focal analysis is shown in Fig. 2; the resulting map shows areas of greatest production.

Regions with more than 250 kt yr⁻¹ within a distance of 50 km occur in southern Australia, concentrations of more than 500 kt yr⁻¹ within 50 km occur in South Australia, western Victoria and central NSW.

As shown in the Fig. 1, there is large annual (spatial and temporal) variation in the amount of crop stubble PAFH that correlates broadly with variation in annual rainfall. Variation across the time series examined (1996–2005) was nearly twofold, with national total potential availability ranging from about 7–38 Mt yr⁻¹. For this 10-year period, on average, about 27 Mt yr⁻¹ of crop stubble is potentially available (with a standard deviation of 8). We have assumed that this average will not change in the future. Individual amounts for each SD, extracted from the 50 m resolution data, can be found in Tables S1–S3. There are 12 SDs with a potential to produce more than 1 Mt of stubble biomass per year.

Grasses

There is extremely high interannual variability in the amount of grass biomass PAFH (Fig. 3). Across the 30-year period modelled, the amount varied from about 1 to 95 Mt yr⁻¹. The mean annual biomass PAFH was about 20 Mt (with a standard deviation of 22 Mt). Variation in land area with harvestable quantities of grass biomass ranged from 0.2 to 19 Mha over the 30 year period and is highly correlated with grass production. Focal analysis, as described above, was carried out for years of contrasting total production to illustrate changes in biomass concentration (Fig. 4).

Tables S1–S3 give the average annual grass biomass PAFH by SD; there are eight SDs with values of approximately 1 Mt or more.

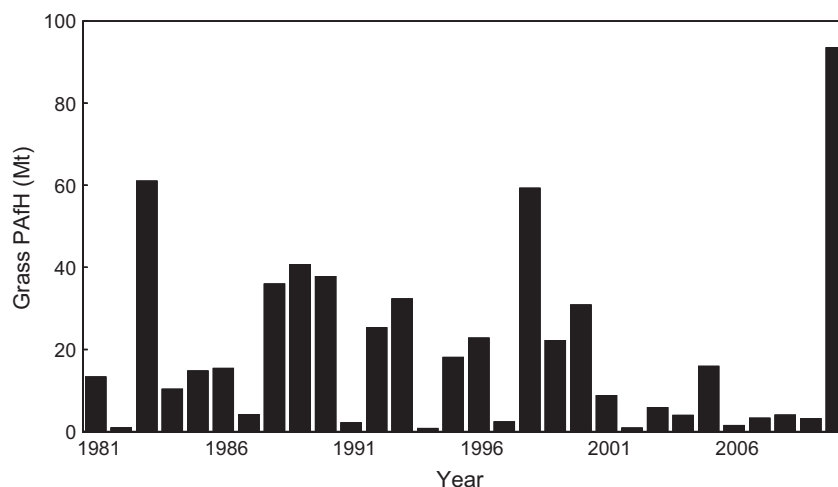


Fig. 3 Interannual variation in grass biomass potentially available for harvest (PAFH) over the period 1981–2010 (from Crawford *et al.*, 2012).

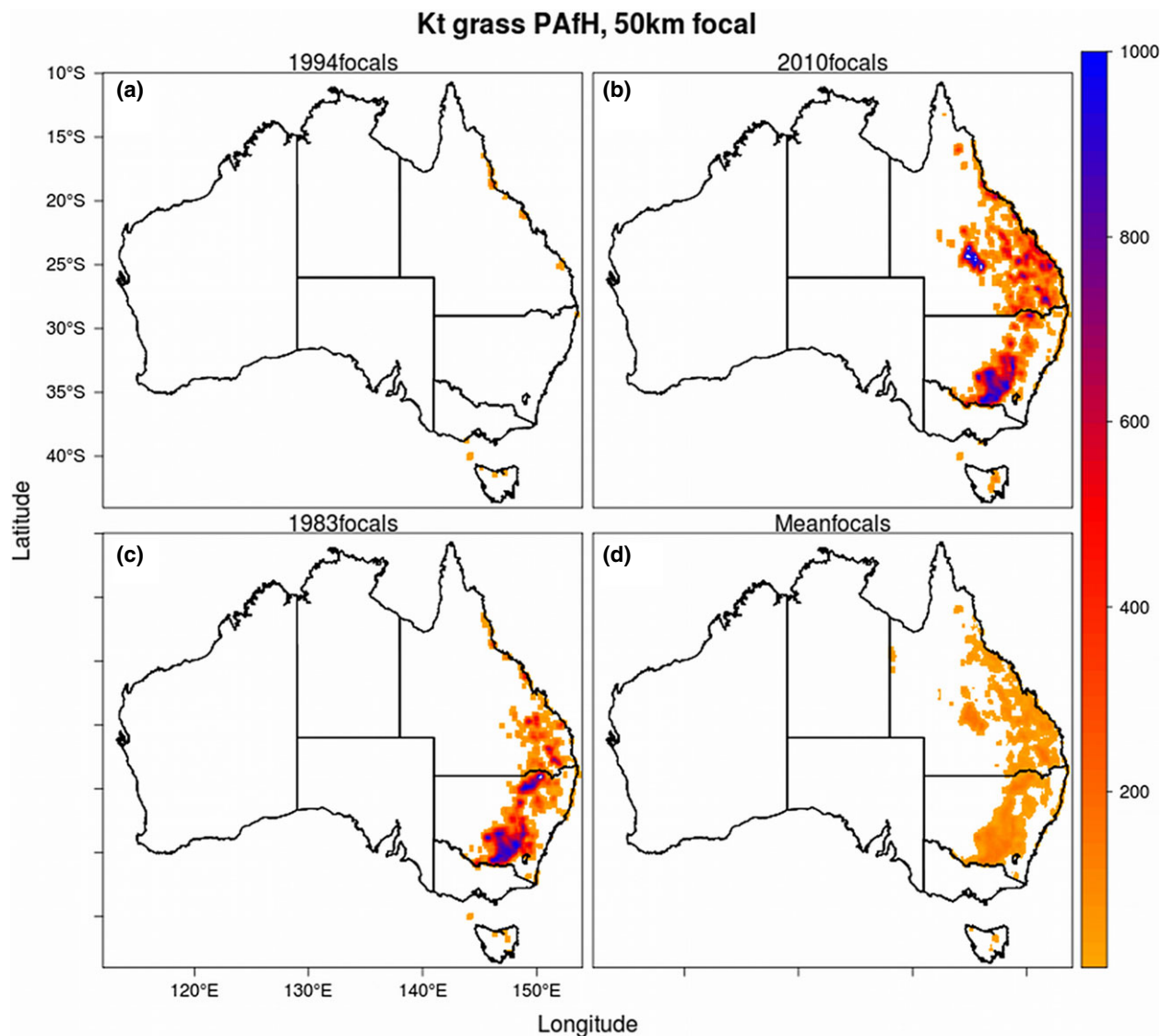


Fig. 4 Grass biomass (kt) potentially available for harvest (PAfH) for focal concentrations of approximately 50 km radius. Data shown for the lowest (a), highest (b), second highest (c) and average (d) year over the period 1981–2010. Areas with PAfH $< 3 \text{ t ha}^{-1}$ are not shown (from Crawford *et al.*, 2012).

Plantation forests

Australia's total plantation area in 2010 was $\sim 2 \text{ Mha}$ (Garvan & Parsons, 2011), distributed within 15 NPI regions (Fig. 5). When mapped to SDs, forest plantations are located in 44 SDs (Tables S1–S3). Gavran *et al.* (2012) assumed little change in future plantation area when forecasting wood supply. Estimated amounts of biomass potentially available from plantations ranged from about 11 to 14 Mt yr^{-1} over the period 2010–2050 (Table 1). For 2010, the potential availability of biomass ranges from 40 kt to over 2.3 Mt between the NPI regions. Four NPI regions have estimated potentially available biomass between 1.2 and 2.3 Mt yr^{-1} . The

Green Triangle and the Murray Valley are major producers of softwood sawlogs and pulpwood. Since the mid 1990s, there has been a concerted effort in establishing hardwood plantations primarily for pulpwood in Western Australia, the Green Triangle and Tasmania. There is a general trend for the annual harvestable wood volume and hence the potential biomass for bioenergy, from these hardwood plantations to increase as the estate matures.

The total biomass potentially available for harvest/diversion from plantation forests is reported at the SD level in Tables S1–S3. Plantation forests could contribute biomass for bioenergy in many of the SDs with an annual contribution greater than 500 kt in at least seven SDs.

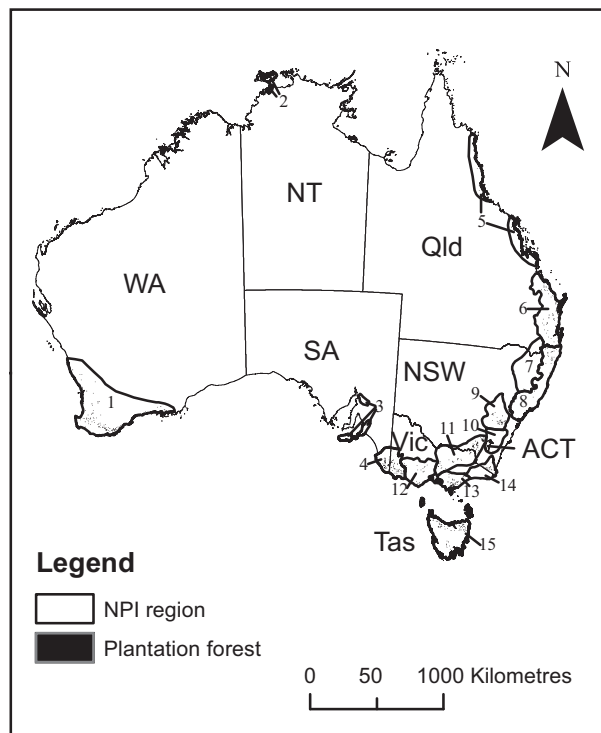


Fig. 5 Map of Australia showing location of 15 National Plantation Inventory (NPI) regions and distribution of the plantation forest resource in 2010.

Native forests managed for sawlog production

Native forests are managed for sawlog (and associated pulp log) production in five Australian states – WA, Qld, NSW, Vic. and Tas. We disaggregated the total production of sawlogs and pulp logs within each state into 19 SD polygons taking into account forest distribution and our broad knowledge of forest management (Raison & Squire, 2010). Figure 6 shows the managed native forests and the SD polygons which cover the sawlog production areas. Managed native forest occurring outside of these polygons is managed for products other than sawlog production.

The amount of biomass potentially available from native forests managed for sawlog as identified above is about 7.9 Mt yr⁻¹ (Table 2) and is assumed to remain constant into the future. High potential availabilities (>1 Mt yr⁻¹) are confined to two SDs in Tasmania.

Bagasse

There are 24 sugar mills concentrated around the sugarcane resource, and the mills fall into the boundaries of six SDs (Fig. 7). It is estimated that there are 5.5 Mt yr⁻¹ of bagasse potentially available (Table 3), and some is already used to generate energy within the mills. The

Table 1 Plantation forest biomass (kt yr⁻¹) potentially available for bioenergy production in 15 National Plantation Inventory Regions

NPI Region	NPI Name	2010	2030	2050
1	Western Australia	2347	2676	2007
2	Northern Territory	367	288	430
3	Mt Lofty Ranges and Kangaroo Island	133	208	115
4	Green Triangle	2334	2968	2610
5	North Queensland	86	189	171
6	South-east Queensland	652	921	873
7	Northern Tablelands	104	120	162
8	North Coast of NSW	181	845	332
9	Central Tablelands of NSW	501	482	506
10	Southern Tablelands of NSW	44	81	78
11	Murray Valley	1211	1199	1207
12	Central Victoria	382	424	354
13	Central Gippsland	570	785	864
14	East Gippsland-Bombala	336	375	319
15	Tasmania	1683	2659	2816
Total		10 932	14 219	12 842

amount of bagasse in each SD ranged from 57 to almost 1900 kt yr⁻¹, and these amounts are assumed to remain constant into the future.

Waste

Estimates of organic waste for MSW, C&I and C&D generated in each state/territory in 2006–07 are shown in Table 4. Only the MSW waste stream was included in calculation of SD waste biomass, reducing the total biomass potentially available by 39% on average across Australia. The MSW waste biomass that was disaggregated to SDs averaged 346 kg/person over a range of 107–829 kg/person across all states and territories (Table 5). Tables S1–S3 give the individual SD quantities for organic MSW based on population. Most SDs were estimated to generate less than 100 kt yr⁻¹ of waste biomass in 2010. Annual estimates for the large capital cities of Brisbane, Melbourne and Sydney ranged from 800 kt to 1 Mt in 2010, rising to 1.4–1.7 Mt in 2050. Estimates for other medium to highly populated areas ranged from >100–600 kt yr⁻¹, increasing to 300 kt to 1.2 Mt in 2050.

New plantings of short-rotation trees (SRT)

There is negligible biomass currently available from SRT crops, but this could increase to about 14 Mt yr⁻¹

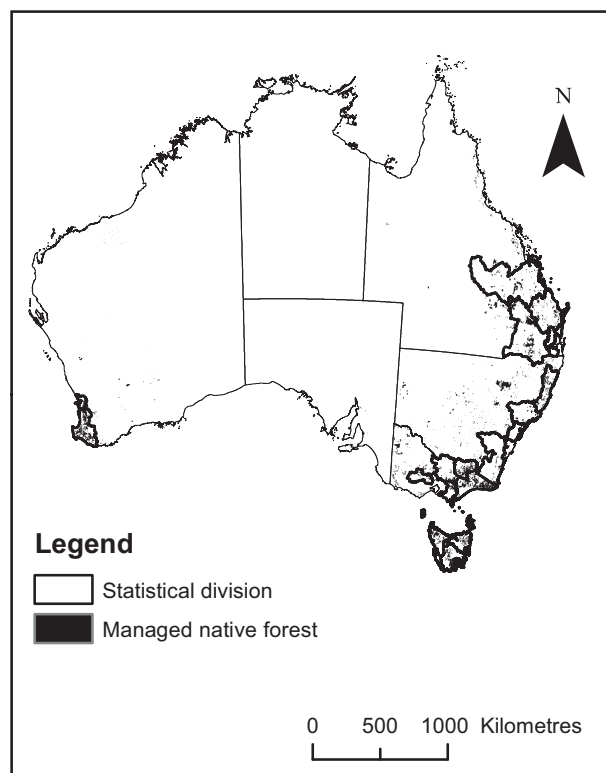


Fig. 6 Distribution of native forest managed for sawlog production within SDs.

by 2030 (Table 6), and this could be doubled by 2050 if a major planting programme (such as the simple 5–10% assumption used in this study) was undertaken. The distribution of cropping and sown pasture lands is quite wide spread in Australia with areas of this land-use type being present in all SDs. Estimated productivity of SRT varied from 2.9 to 19.5 t ha⁻¹ yr⁻¹. Thirty-six SDs each could have 10 000 ha or more planted to SRT in the 5% planting scenario. If these very simple scenarios were to be explored in more regionally specific feasibility studies, the economics would probably dictate that a more concentrated resource should be developed around proposed facilities (rather than a randomized 5% smear across the SD) to benefit from economies of scale and density (e.g. Brinsmead *et al.*, 2015a).

Aggregated total annual availability of biomass

The total annual amount of biomass potentially available from all feedstock types (under the assumptions used in this study) is 78 Mt, increasing to almost 100 Mt in 2030 and 114 Mt in 2050 (Table 7). Crop stubble and grasses are the current main sources of potentially available biomass. If an SRT estate as explored in this paper was established, it could potentially produce

Table 2 Annual potential availability (kt) of biomass from native forests for each important SD

SD ID	SD Name	State	Biomass
105	Sydney	NSW	72
110	Hunter	NSW	216
125	Mid-north coast	NSW	721
145	South-eastern	NSW	433
220	Central Highlands	Vic.	170
240	Goulburn	Vic.	255
245	Ovens-Murray	Vic.	170
250	East Gippsland	Vic.	682
255	Gippsland	Vic.	426
309	Sunshine Coast	Qld	29
312	West Moreton	Qld	58
315	Wide Bay-Burnett	Qld	87
320	Darling Downs	Qld	87
330	Fitzroy	Qld	29
505	Perth	WA	65
510	South-west	WA	586
610	Southern	Tas.	2314
615	Northern	Tas.	1157
620	Mersey-Lyell	Tas.	385
Total			7942

an amount of biomass similar to crop stubble by 2050. Organic waste would increase over time as the population is predicted to increase.

The total feedstock amounts for each SD now and into the future are shown in Figs 8–10. The contribution of each feedstock type to the biomass for each SD is given in Tables S1–S3. Fifteen individual SDs from Western Australia, Queensland, NSW and Tasmania could produce more than 2 Mt yr⁻¹ of biomass potentially available for harvest/diversion, with two of the NSW SDs potentially producing more than 4 Mt yr⁻¹ (Fig. 8, Table S1). With the addition of biomass from SRT, the number of SDs able to produce more than 2 Mt yr⁻¹ of biomass PAfH increases to 22 in 2030 and 25 in 2050 with two and then three SDs potentially producing more than 5 Mt yr⁻¹ (Figs 9 and 10, Tables S2 and S3).

Discussion

In this study, we have only included quantities of biomass PAfH on an assumed ongoing (sustainable yield) basis. Some constraints have been applied to the amount potentially available for harvest (for example, rudimentary protection of environmental values, or on an economic basis where in forests the high-value sawlog component was not considered to be available). For forests, all pulp logs and saw mill residue were considered potentially available for diversion to bioenergy. In-field woody harvest residues are not currently harvested, but

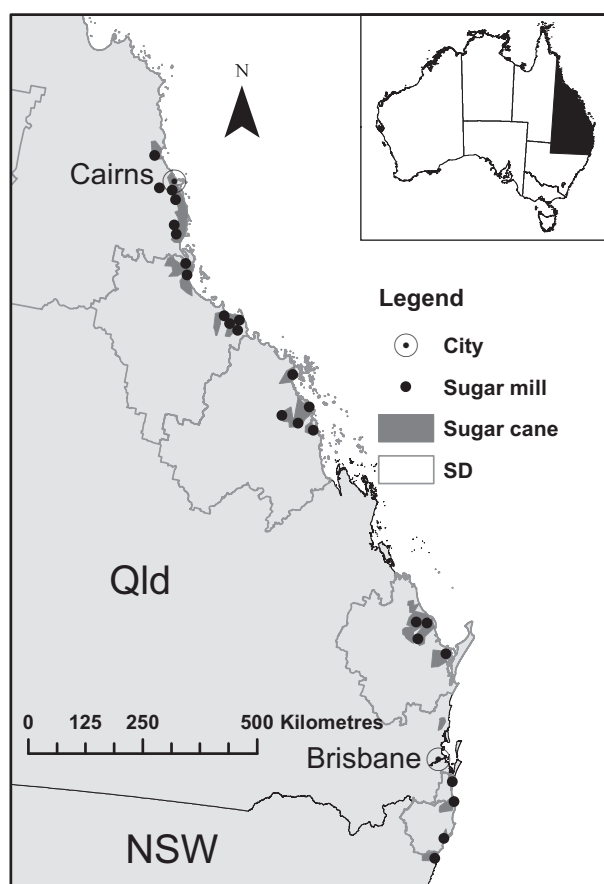


Fig. 7 Map showing distribution of sugarcane and location of sugar mills in Queensland and northern New South Wales. The statistical division boundaries containing the sugar mills are also shown. (Sugarcane and mill information modified from ASMC, 2014).

Table 3 Annual potential availability (dry kt) of bagasse by Statistical Division

SD ID	SD Name	State	Biomass
120	Richmond-Tweed	NSW	349
307	Gold Coast	Qld	57
315	Wide Bay-Burnett	Qld	759
340	Mackay	Qld	1387
345	Northern	Qld	1869
355	Far North	Qld	1081
	Total		5502

conservative estimates of what could be collected are included as potentially available for harvest. All foliage and small branches are retained in the forest.

In aggregate, the biomass types considered in this study could make a significant contribution to the amount of biomass potentially available for harvest/diversion. Stubble and grasses were the largest biomass

Table 4 Annual amounts of organic waste (kt) by stream by state/territory 2006–2007 (from Hyder, 2013). Streams: MSW (municipal solid waste), C&I (commercial and industrial waste) and C&D (construction and demolition waste)

State/Territory	MSW	C&I	C&D	Total
NSW	1538	1993	481	4012
Vic.	1432	967	167	2566
Qld*	1889	79	32	2000
WA	844	562	57	1463
SA	481	233	67	781
Tas.	53	22	NR	75
ACT	281	72	1	354
NT	28	NR	NR	28
Total (min.)	6546	3928	805	11 279

NR, not reported.

*For Queensland, disposal data were estimated from recycled amounts.

Table 5 Annual amounts of organic MSW (from Hyder, 2013) by state for 2006–2007 per capita (kg person⁻¹) (population data from DEWHA, 2010)

State/Territory	Population	Organic MSW per capita
NSW	6 888 000	223
Vic.	5 205 000	275
Qld	4 181 000	452
WA	2 106 000	401
SA	1 584 000	304
Tas.	493 000	108
ACT	340 000	828
NT	215 000	130

types (combined, they account for 60% of the 2010 total biomass). However, these types are the most widely distributed with relatively low biomass spatial density, providing economic and logistic challenges for harvesting and transport. Stubble and grasses are also only physically harvestable for part of the year (due to technical constraints), so that storage may be important if they are to be fully utilized (unless they are combined with other types of biomass throughout the year). For grasses, harvesting in the summer rainfall part of Australia (i.e. subtropics) is after the wet season, from March to May. During the wet season, harvesting is generally not possible due to the impact of machinery on soil. The beginning of the dry season is the ideal time for maximizing harvest amounts, after this the biomass decays. In the southern winter rain areas, harvesting takes place as soon as there is sufficient grass biomass on the ground and coincides with grain harvest in about November–December, or slightly earlier in the more northern zones. For harvest of green biomass (i.e.

Table 6 The area (ha), biomass (kt) and average productivity ($\text{t ha}^{-1} \text{yr}^{-1}$) corresponding to planting of 5% of crop and pasture land to SRT in each statistical division. SDs with more than 10 000 ha that could be planted to SRT are bolded.

SD ID	SD Name	Area	Biomass	Productivity
105	Sydney	110	1	9.1
110	Hunter	915	7	7.7
115	Illawarra	455	7	15.4
120	Richmond-Tweed	2415	47	19.5
125	Mid-North Coast	880	15	17.0
130	Northern	84 145	648	7.7
135	North-western	87 635	504	5.8
140	Central West	75 725	457	6.0
145	South-eastern	11 415	97	8.5
150	Murrumbidgee	64 230	352	5.5
155	Murray	39 225	194	4.9
160	Far West	150	<1	–
205	Melbourne	11 675	122	10.4
210	Barwon	25 410	185	7.3
215	Western District	77 455	719	9.3
220	Central Highlands	38 030	289	7.6
225	Wimmera	112 075	544	4.9
230	Mallee	106 895	311	2.9
235	Loddon	38 895	227	5.8
240	Goulburn	58 935	462	7.8
245	Ovens-Murray	19 460	205	10.5
250	East Gippsland	19 680	175	8.9
255	Gippsland	22 085	357	16.2
305	Brisbane	280	2	7.1
307	Gold Coast	465	8	17.2
309	Sunshine Coast	345	6	17.4
312	West Moreton	970	9	9.3
315	Wide Bay-Burnett	5500	73	13.3
320	Darling Downs	69 705	695	10.0
325	South-west	20 045	157	7.8
330	Fitzroy	31 325	336	10.7
335	Central West	350	2	5.7
340	Mackay	17 015	163	9.6
345	Northern	5125	43	8.4
350	Far North	8085	91	11.3
355	North-west	140	<1	–
405	Adelaide	1650	11	6.7
410	Outer Adelaide	33 795	233	6.9
415	Yorke and Lower North	74 370	352	4.7
420	Murray Lands	95 850	365	3.8
425	South-east	74 805	566	7.6
430	Eyre	139 175	519	3.7
435	Northern	40 270	169	4.2
505	Perth	4595	55	12.0
510	South-west	31 150	359	11.5
515	Lower Great Southern	118 165	693	5.9
520	Upper Great Southern	155 880	752	4.8

(continued)

Table 6 (continued)

SD ID	SD Name	Area	Biomass	Productivity
525	Midlands	299 785	1403	4.7
530	South-eastern	76 430	393	5.1
535	Central	134 640	690	5.1
540	Pilbara	160	<1	–
545	Kimberley	445	3	6.7
605	Greater Hobart	1435	10	7.0
610	Southern	12 650	99	7.8
615	Northern	22 950	264	11.5
620	Mersey-Lyell	10 170	163	16.0
705	Darwin	450	6	13.3
710	Northern Territory – Bal	3645	37	10.2
805	Canberra	545	5	9.2
810	Australian Capital Territory – Bal	355	4	11.3
Totals		2 390 610	14 661	

Table 7 Total biomass (Mt) potentially available annually for each feedstock and time period

Biomass type	2010	2030	2050
Crop stubble	27.7	27.7	27.7
Grasses	19.7	19.7	19.7
Plantation forests	10.9	14.2	12.8
Native forests	7.9	7.9	7.9
Bagasse	5.5	5.5	5.5
Organic waste (MSW)	6.5	9.0	10.9
SRT	0.0	14.7	29.3
Total	78.3	98.7	114.0

no drying required) which is useful for biogas production, timing would be similar because farmers will target harvest at the time of optimum biomass accumulation.

A further challenge results from the considerable interannual variability of production of grass and crop stubble, especially for grasses. Woody biomass sources are less variable and provide a 'buffer' supply, because biomass accumulates over time and can be effectively 'stored' in the field until required. Therefore, combining woody biomass sources with crop residues/grass can help spread the risk of the effects of climatic variability on biomass production and potential availability.

Our estimates of forest biomass (woody biomass), which already exclude sawlogs, are likely to be maximum amounts that could be potentially available for use for bioenergy. There are existing alternative markets for pulpwood and for a portion of sawmill residues in many regions (e.g. Rodriguez *et al.*, 2011c). Thus, bioenergy would compete with these markets if the biomass

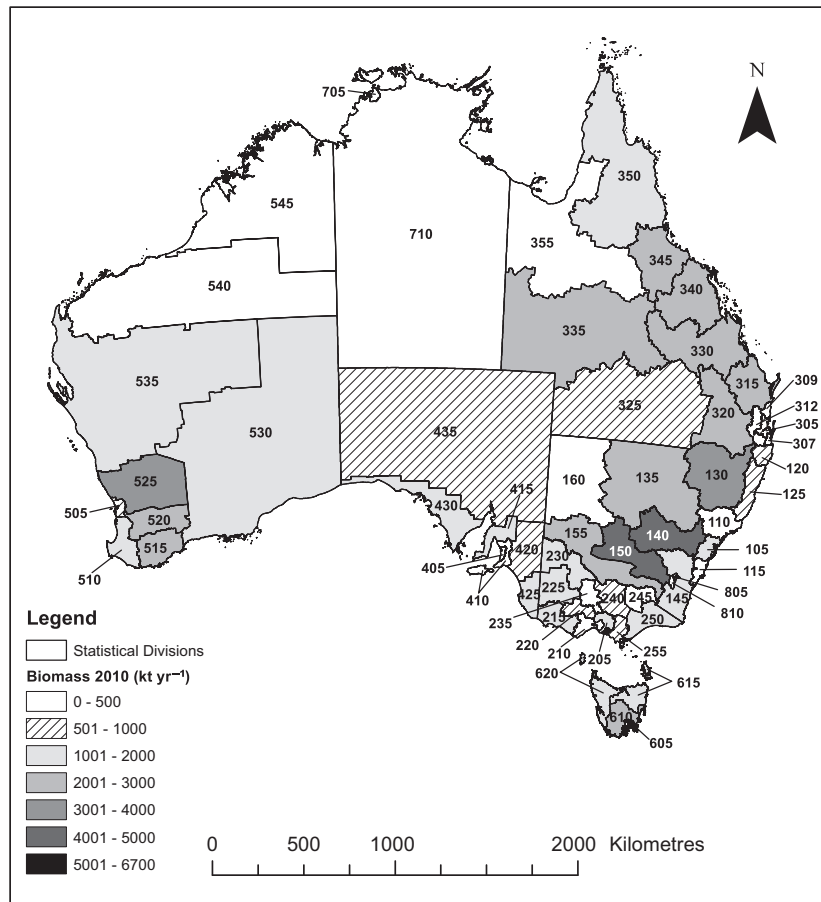


Fig. 8 Spatial representation of the potential total biomass (kt) potentially available annually in each of the 60 Statistical Divisions in 2010.

resource was to be diverted. Currently, in-field forest residues are not collected and the impact of removal of these fractions will require careful management and further research. Further work is required to develop harvesting systems to improve collection efficiency, quantify the costs and explore the sustainability implications of removing the biomass from the forest floor.

Much of the bagasse produced is already used in the sugar mills to generate bioelectricity. Our estimates of the amounts of bagasse potentially available for diversion include the bagasse already used for bioelectricity.

All organic waste resources produced in Australia were considered to be potentially available for diversion to bioenergy – yet at present over 51% of waste generated in Australia is recycled (DEWHA 2010). Only the organic MSW waste was disaggregated to SDs. This biomass type is a relatively minor component of the seven types identified in this study – it is assumed to contribute 8% by mass in 2010, increasing to ~10% by 2050. The organic material in the C&I and C&D waste streams – an additional 4.7 Mt of organic biomass in

2010 – has been excluded because available data cannot be disaggregated satisfactorily to SD level. As recycling and recording of these waste streams improves, there is potential for available quantities to increase. Regardless of the amount of waste biomass potentially available, the most significant biomass hotspots are those rural SDs that produce both agricultural and forestry biomass resources.

The planting of SRT for biomass is one suggested way of increasing the amount of biomass potentially available for bioenergy into the future. The SRT productivity values given in Table 6 are the average for identified land in each SD. The actual productivity achieved would depend on where SRT were planted and may be higher than the average if the growers selected the more productive areas. A major investment would be required to establish an SRT estate of the magnitude estimated in the scenarios for this study. It is unlikely that an establishment rate would exceed 100 000 ha yr⁻¹ (achieved with establishment of blue gum plantations over several years during the managed

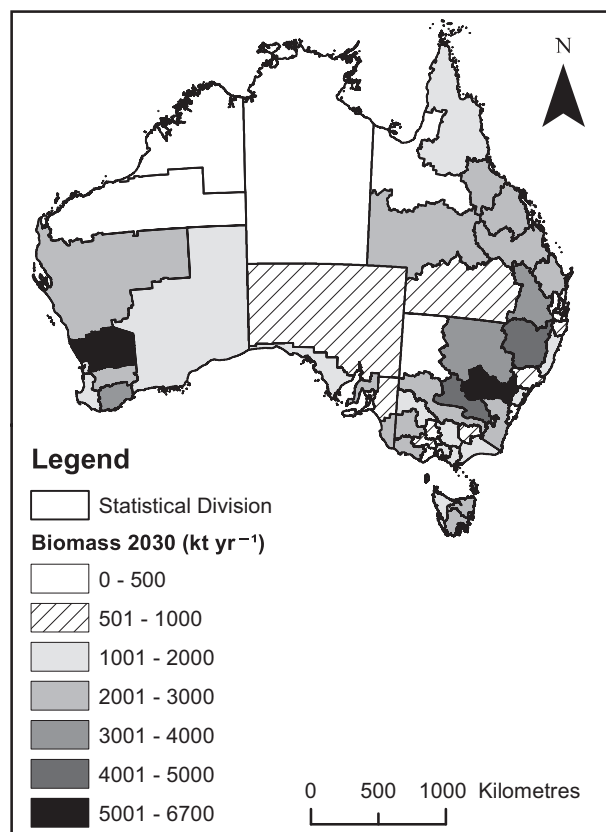


Fig. 9 Spatial representation of the potential total biomass (kt) potentially available annually in each of the 60 Statistical Divisions in 2030. See Fig. 8 for individual SD numbering.

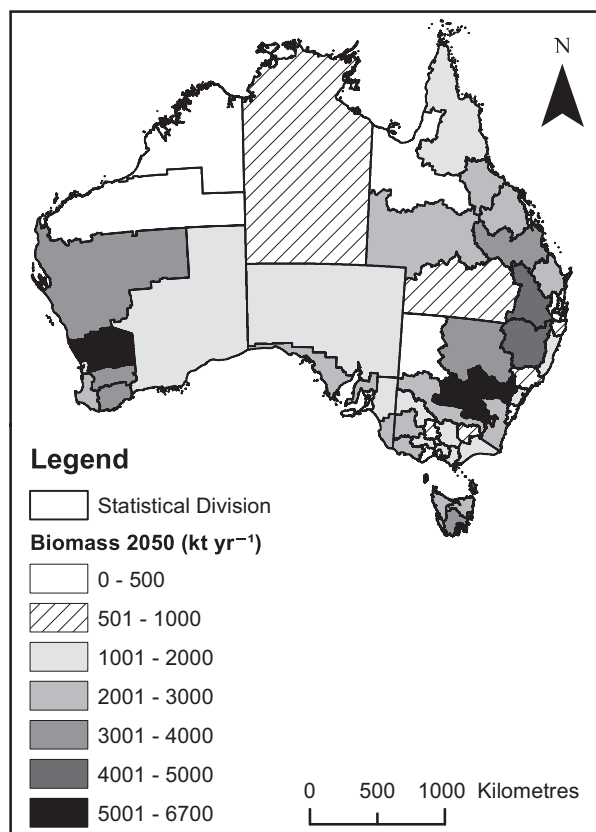


Fig. 10 Spatial representation of the potential total biomass (kt) potentially available annually in each of the 60 Statistical Divisions in 2050. See Fig. 8 for individual SD numbering.

investment schemes (MIS) expansion of the last decade). Thus, it will take decades of investment and effort to achieve the area of 2.4 Mha estimated in this scenario.

Woody regrowth biomass has not been assessed in this study, but is known to be significant in particular regions of Australia such as in the Fitzroy Basin in central Queensland (Booth *et al.*, 2014; Murphy *et al.*, 2015).

There are many different existing and developing technologies for producing electricity, liquid fuel, gas and other products from lignocellulosic biomass. Depending on the type of technology, there are trade-offs between the type and scale of economy of the conversion facility, and the spatial distribution and concentration of the feedstock resource (e.g. Richard, 2010; Stucley *et al.*, 2012; Brinsmead *et al.*, 2015a). Brinsmead *et al.* (2015a) suggest specific analytical approaches to define the economic tradeoffs between spatial density, cost of harvest and transport, and scale of economy for a range of emerging technologies. Richard (2010) suggests that a cellulosic biofuel refinery should have an annual output of 200–1000 ML in order to achieve economies of scale. IEA (2004) reports conversion

efficiencies of cellulosic biomass, such as the types discussed here, to be in the range of 288–390 l of ethanol per tonne of dry feedstock. Using this range, a 200 ML refinery would require 500–700 kt of biomass per year. Richard (2010) reports that a 300 MW power plant would require a similar amount of biomass. Optimizing the variables within the production plant, including cost and scale efficiency, needs to be conducted in the context of the supply chain and region, in terms of biomass spatial density, type, seasonality etc. as demonstrated by Brinsmead *et al.* (2015a,b). This approach can be further explored across the range of biomass types and regions matched with energy types and scales.

In our assessment of biomass potentially available for harvest/diversion on a SD basis for 2010, 41 of the 60 SDs produced in excess of 500 kt yr⁻¹. However, a full analysis of the constraints imposed by the logistics of harvest, storage and transport, or by economics has not been applied and is not discussed in this paper. Stucley *et al.* (2012) indicate that a typical breakdown of costs for producing and supplying biomass for bioenergy would be 25% for production, 50% for harvesting and

25% for transport. Bioenergy industries will require large amounts of biomass to be sustainably produced and supplied in a reliable manner to conversion facilities. Clearly, there are major challenges in developing biomass supply systems at the scale required to make a major contribution to a renewable bioenergy market. The approach taken by Brinsmead *et al.* (2015a,b) and Rodriguez *et al.* (2011a) could be applied at a national scale across the aggregate biomass PAFH, along with more detailed surveys of cost structures relevant to each region.

Our analyses provide a broad assessment of the potential availability of biomass for bioenergy in Australia; they have increased the resolution of information (i.e. finer scale) and are therefore useful in guiding potential government interaction and business development. More detailed regional analyses, including the transport and storage costs of delivered biomass, as well as competing markets for biomass, are needed to underpin investment in specific conversion facilities. More detailed regional investigations of the sustainability of various supply chains are also required (O'Connell *et al.*, 2013; Future Farm Industries CRC, 2014).

Acknowledgements

We thank our CSIRO colleagues particularly fellow members of the Sustainable Biomass Project and Dr Paul Graham for their inputs to the development of this paper and Dr Trevor Booth and Dr Jenny Haywood for their critical reviews. This work spawned from a project funded by AEMO's 100% renewable electricity scenarios project and was funded by the CSIRO Energy Flagship.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Biomass potentially available (kt yr⁻¹) in 2010 from each assessed biomass type for bioenergy production in 60 Australian Statistical Divisions.

Table S2. Biomass potentially available (kt yr⁻¹) in 2030 from each assessed biomass type for bioenergy production in 60 Australian Statistical Divisions.

Table S3. Biomass potentially available (kt yr⁻¹) in 2050 from each assessed biomass type for bioenergy production in 60 Australian Statistical Divisions.